Texas A&M University
Department of Electrical and Computer Engineering

ECEN 689 – Optical Interconnects

Spring 2016

Exam #2

Instructor: Sam Palermo

- Please write your name in the space provided below
- Please verify that there are **7** pages in your exam
- You may use <u>one</u> double-sided page of notes and equations for the exam
- Good Luck!

Problem	Score	Max Score
1		35
2		30
3		35
Total		**100**

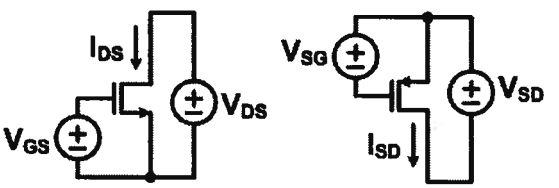
Name: SAM PALERMO

UIN: _____

Table 4.1 Numerical relationship between Q and bit-error rate.

Q	*BER*	Q	*BER*
0.0	1/2	5.998	10^{-9}
3.090	10^{-3}	6.361	10^{-10}
3.719	10^{-4}	6.706	10^{-11}
4.265	10^{-5}	7.035	10^{-12}
4.753	10^{-6}	7.349	10^{-13}
5.199	10^{-7}	7.651	10^{-14}
5.612	10^{-8}	7.942	10^{-15}

Key MOS Equations



Saturation: $NMOS\ I_{DS} = \frac{1}{2} KP_N \frac{W}{L} (V_{GS} - V_{TN})^2$

Saturation: $PMOS\ I_{SD} = \frac{1}{2} KP_P \frac{W}{L} (V_{SG} - |V_{TP}|)^2$

Triode: NMOS $I_{DS} = KP_N \frac{W}{L} \left(V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS}$

Triode: $PMOS\ I_{SD} = KP_P \frac{W}{L} \left(V_{SG} - |V_{TP}| - \frac{V_{SD}}{2} \right) V_{SD}$

$$NMOS\ g_m = \frac{\partial I_{DS}}{\partial V_{GS}},\quad PMOS\ g_m = \frac{\partial I_{SD}}{\partial V_{SG}}$$

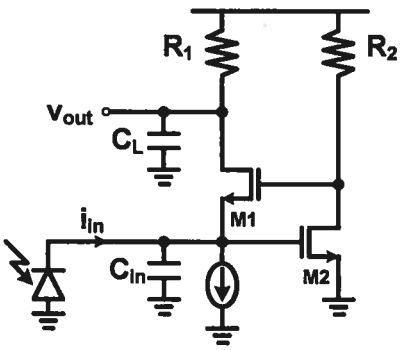
$$NMOS\ g_o = \frac{\partial I_{DS}}{\partial V_{DS}},\quad PMOS\ g_o = \frac{\partial I_{SD}}{\partial V_{SD}}$$

Problem 1 (35 points)

For the TIA shown below, assume that all transistors are operating in saturation with $r_o=\infty$. Obtain expressions for the following:

a) Low-Frequency Transimpedance.

b) The TIA's input bandwidth. Note, it's OK to neglect the transistor capacitors here.



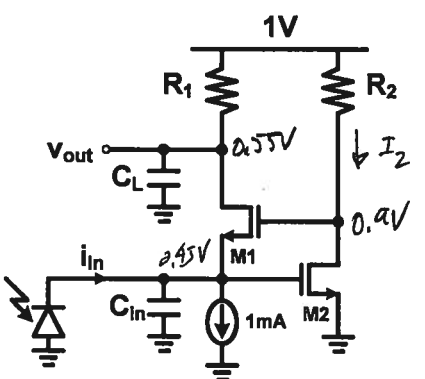
a. $R_T = R_1$

b. $R_{in} = \dfrac{1}{g_{m1}(1+g_{m2}R_2)}$

$\omega_{in} = \dfrac{1}{R_{in}C_{in}} = \dfrac{g_{m1}(1+g_{m2}R_2)}{C_{in}}$

c) Now assume that the TIA works with a 1V supply and 1mA bias in the input stage. Assume that all the transistors have an overdrive voltage of 100mV. What is the minimum input resistance and maximum transimpedance that can be achieved, while still keeping all transistors in saturation? Use the following NMOS parameters.

$KP_N=\mu_nC_{ox}=600\mu A/V^2$, $V_{TN}=0.35V$, $\lambda_N=0V^{-1}$



$g_{m2} = \dfrac{2I_2}{V_{OD}}$ $R_2 = \dfrac{100mV}{I_2}$

$g_{m2}R_2 = \left(\dfrac{2I_2}{V_{OD}}\right)\left(\dfrac{100mV}{I_2}\right) = 2$

$g_{m1} = \dfrac{2(1mA)}{100mV} = 20mA/V$

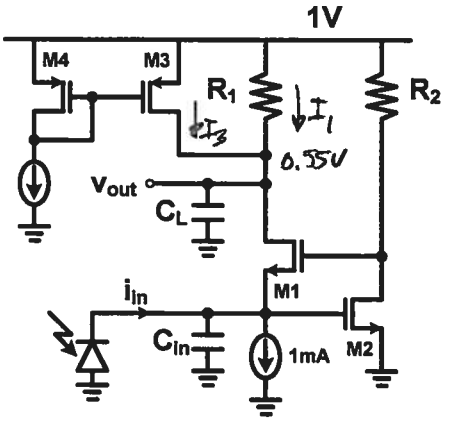
$R_{in,min} = \dfrac{1}{20mA/V(1+2)} = 16.7\Omega$

$Max\ R_T = Max\ R_1 = \dfrac{1V-0.55V}{1mA} = 450\Omega$

$R_{in,min} = 16.7\Omega$

$R_{T,max} = 450\Omega$

d) Now assume that the circuit is modified as shown below. Assuming the same NMOS bias conditions as part (c), how much current should flow through M3 to allow the TIA to achieve 60dBΩ transimpedance?



For $R_1 = 1k\Omega$

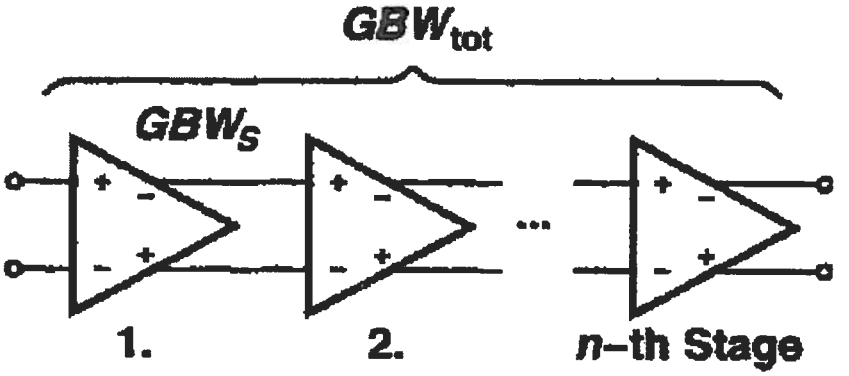
$$I_1 = \frac{1V - 0.55V}{1k\Omega} = 450\mu A$$

$$I_3 = 1mA - I_1 = 550\mu A$$

$I_{M3} =$ 550μA

Problem 2 (30 points)

Assume that the limiting amplifier below consists of cascaded identical single-pole amplifier stages, with gain A_{vs} and bandwidth ω_{3dBs}.



a) Design the limiting amplifier to achieve a 46dB total gain and 25GHz total bandwidth with the minimum per-stage gain-bandwidth product. Give the stage number and the per-stage gain and bandwidth. Also compute the per-stage gain-bandwidth product.

For minimum per-stage GBW (maximum GBW w/a certain stage GBW)

$n_{opt} = 2\ln(G_{tot}) = 2\ln(200) = 10.6 \Rightarrow$ Use 11 stages

w/ $n = 11$ $\quad A_{VS} = \sqrt[11]{200} = 1.62$

$$\omega_{3dB,tot} = \omega_{3dBs}\sqrt{2^{1/n}-1} \Rightarrow \omega_{3dBs} = \frac{\omega_{3dB,tot}}{\sqrt{2^{1/n}-1}}$$

$$\omega_{3dBs} = \frac{2\pi(25GHz)}{\sqrt{2^{1/11}-1}} = 616\ Grad/s = 98.06GHz$$

n = 11

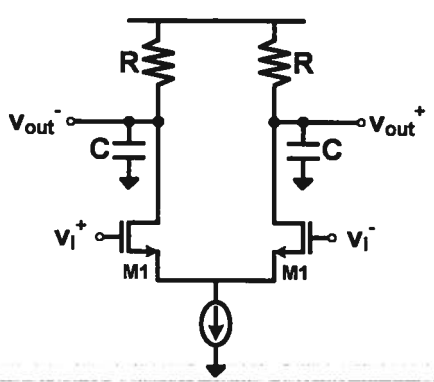
A_{vs} = 1.62

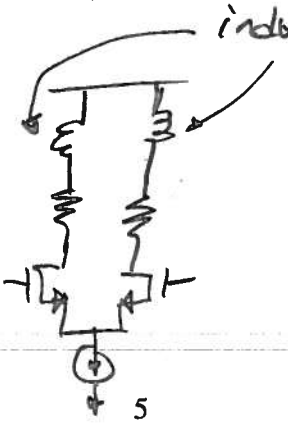
ω_{3dBs} = 616 Grad/s (98.06 GHz)

GBW_s = 9976 rad/s (1596 GHz)

b) Assume that the simple differential amplifier stage shown below can only achieve a maximum GBW_s=100GHz. Propose a change to the stage design below to achieve the required GBW_s from part (a).

One possible approach is to add shunt peaking inductors

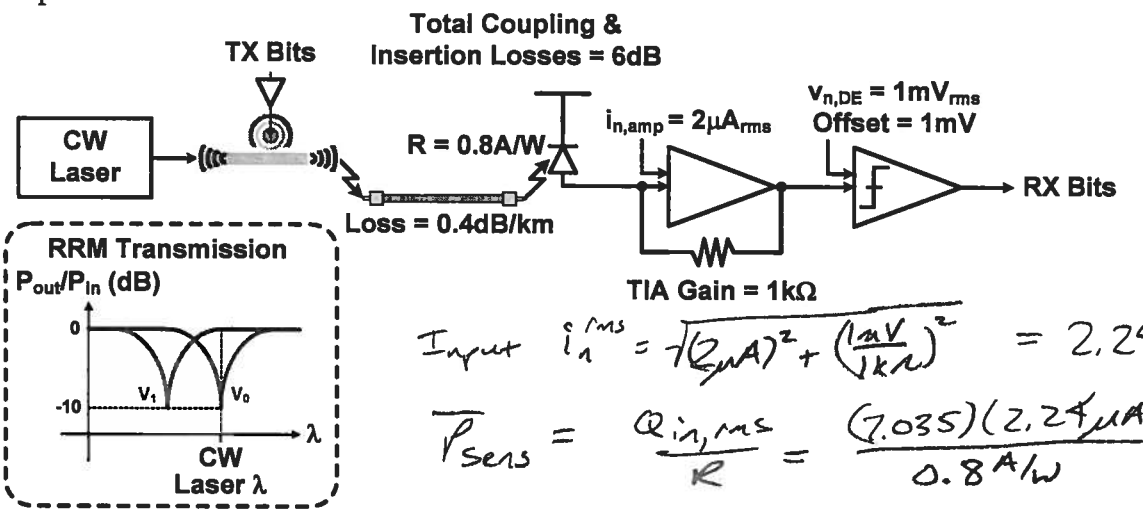




w/ $L = \frac{R^2C}{2.41}$ can increase BW by 72% w/ no peaking in magnitude response

Problem 3 (35 points)

A 25Gb/s optical interconnect system uses a ring resonator modulator transmitter that can achieve a 10dB extinction ratio to transmit data over a 2km fiber. The optical receiver has 1kΩ gain and the following noise/offset components shown below. The link has an additional total coupling and insertion loss of 6dB. Assume that we can neglect the photodetector noise and fiber dispersion.



Input $i_n^{rms} = \sqrt{(2\mu A)^2 + \left(\frac{1mV}{1k\Omega}\right)^2} = 2.24\mu A$

$\overline{P_{sens}} = \frac{Q\, i_{n,rms}}{R} = \frac{(7.035)(2.24\mu A)}{0.8\,A/W} = 19.7\mu W = -17.1dBm$

a) What is the required CW Laser output power to achieve a BER=10^{-12}?

Loss/Penalties: * offset → $V_{spp} = (1k\Omega)(2)(7.035)(2.24\mu A) = 31.5mV$

$\delta = \frac{1mV}{31.5mV} = 0.032$ $PP_{offset} = 1 + 2\delta = 1.063 = 0.27dB$

* Fiber Loss = (0.4dB/km)(2km) = 0.8dB * Coupling/Ins = 6dB

* $PP_{ER} = \frac{ER+1}{ER-1} = \frac{10+1}{10-1} = 1.222 = 0.87dB$ Total Loss/Penalties = 7.94dB

$\frac{P_1 + \frac{P_1}{10}}{2} = 121\mu W$

$\overline{P_{TX}} = \frac{\overline{P_{sens}}}{Loss/Penalties} = -17.1dBm + 7.94dB = -9.16dBm = 121\mu W$

$P_{CW} = -6.56dBm = 221\mu W$

b) Assume that the CW laser has a 10% wall-plug efficiency, the TX power efficiency is 1pJ/bit, and the RX power efficiency is 0.7pJ/bit. What is the total link power efficiency?

CW laser Power = $\frac{221\mu W}{0.1} = 2.21\mu W$

TX Power = 25mW

RX Power = 17.5mW

$P_{eff} = \frac{42.72}{25Gb/s} = 1.71pJ/bit$

c) Now assume that the coupling and insertion loss component, which was previously 6dB, increases to 15dB. What is the total link power efficiency now?

Now P_{CW} must increase by 9dB ⇒ $P_{CW} = 2.44dBm = 1.75mW$

CW laser Power = $\frac{1.75mW}{0.1} = 17.5mW$

$P_{eff} = \frac{60mW}{25Gb/s} = 2.4\,pJ/bit$

Scratch Paper